Absolute Measurement and the Second Quantification of Physics

By: Mitchell, Daniel

By introducing the notion of a "second quantification of physics," this paper makes an original historiographic contribution to the history of physics and philosophy of measurement. In outline, the second quantification begins in the 1840s with the attempts of Gauss and Weber to ensure the global comparability of measurements of terrestrial magnetism, and closes with the outsourcing of standardization work from the physics laboratory to the newly-created national metrological institutes of the 1890s and 1900s. The most critical phase took place between 1863 and 1881. During this time, physicists working through the British Association for the Advancement of Science under the de facto leadership of William Thomson integrated measuring scales for physical quantities into a system of so-called "absolute" units and obtained its international sanction. Their "CGS" (centimetre-gramme-second) system ultimately supplied the basis for modern metrology (Quinn 2017).

The integration of measuring scales, or the invention of absolute units, more than any other feature distinguishes the second quantification from the traditional quantification of physics that historians locate within the period 1780–1830. During this time, many quantitative physical concepts, such as latent heat and electrical capacity, were defined and operationalized (Heilbron 1993; Frängsmyr et al. 1990). Conventional historiography incorporates this process into the development of a unified mathematical-experimental methodology that provides a de facto "big picture" of nineteenth century physics (Buchwald and Hong 2003, cf. Simon 2016). This big picture has made the profound changes to the theoretical structure of measurement that I argue characterized the second quantification difficult to spot (see e.g. Smith and Wise 1989). Departures from the big picture relating to the development of units and standards have largely taken the form of socio-institutional microstudies, which are inherently unsuitable for identifying long-term epistemological trends like a second quantification (e.g. Schaffer 1995; O'Connell 1993). Existing work in integrated HPS has sought to explain the specificity of the epistemic challenges involved in the historical construction of measuring scales for individual physical quantities (Miyake 2017; Chang 2004) without, however, bringing in the need to co-ordinate activity across epistemic discontinuities between different communities of practice (cf. Galison 1997; Star and Griesemer 1989).

With this historical and philosophical background in mind, I offer three reasons why the second quantification merits the name, and indicate, however briefly, how historically it gave rise to recognized issues in the philosophy of measurement relating to units, quantities, and dimensions:

1. The substantiveness of the conceptual, physico-mathematical and operational issues involved in the historical definition and realization of absolute units. Several overlapping criteria can be identified for a unit to be "absolute" (cf. Mitchell 2017):

a) reduction: all measurements must ultimately be traceable to "fundamental" units of mass, length, and time via a network of empirical laws.

b) economy: a "coherent" selection of units that eliminated conversion coefficients. For example, unit velocity would be unit length traversed in unit time.

c) objectivity: the fundamental units should be linked to unchanging features of nature. Historically this produced a shift from artefacts to properties of the Earth, and then to properties of atoms and fundamental constants.

The practice of absolute measurement consisted in the development of experimental protocols that realized these criteria, the construction or employment of measurement standards based upon them, and the associated expression of the numerical results of measurement in forms specially adapted to the unique mathematical properties arising from (a) and (b). I locate the ambiguous physico-mathematical status of “fundamental physical constants” (see e.g. Riordan 2014) in the inability to reconcile the numerical values of measurements of static and current electricity. The mathematical conversion factors introduced by Maxwell as a temporary solution in violation of (b) came to be seen as denoting properties of a medium that transmitted electrical (and magnetic) force.

2. The development of novel algebraic practices for representing physical quantities and the results of measurement in experimental physics. In conformity with (a), modern metrology allows for the algebraic expression of the numerical results of measurement in terms of a dimensional formula that indicates the variation of a derived quantity with the fundamental or “base” units. One Newton (N) of force, for example, can be expressed as 1 m.kg.s-2. At the time of Maxwell’s invention of the dimensional formula (1863), however, algebraic operations had only been defined for numbers and not physical units. To validate these forms required Maxwell to introduce a syntactic mode of mathematical intelligibility from higher mathematics into the practical algebra of physical measurement. This mode was wholly foreign to experimental physicists, who took for granted that mathematical symbols and operations would correspond to physically-realizable ones. Controversies developed between the followers of Maxwell and those of Thomson, who opposed the modern forms. Unlike previous historico-philosophical analyses (de Courtenay 2015; de Boer 1994/5), these findings open up distinct components of the process by which the modern quantity calculus was developed for study, and provide a framework for explaining why these components were not brought together until after the First World War.

3. The pursuit of a widespread program of theoretical and experimental implementation among many different types of physical practitioners. Securing the long-term future of absolute units required physicists to convince other professional groups of their necessity and transmit a raft of relevant cognitive and practical skills. I describe how this demanded the development of new pedagogical tools and rhetorical devices, and explain why it took decades of persistence. Telegraph engineers, for instance, struggled with a fundamental conceptual distinction between a unit and a material standard. They consequently reacted with incredulity when informed that electrical resistance in absolute (electromagnetic) units could be expressed “as a velocity,” or in so many metres-per-second, in conformity with the dimensional formula LT-1 (Mitchell 2017). I explain briefly how ambiguities in the meaning of dimensional formulae and their relationship to units and physical quantities (see e.g. Sterrett, forthcoming) can be traced to attempts to bridge the gulf in intelligibility between physicists and telegraph engineers.

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